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RESEARCH ARTICLE

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The impact of coastal flooding on agriculture: A case-study of Lincolnshire, United Kingdom

Iain J. Gould¹  | Isobel Wright¹ | Martin Collison^{1,2} | Eric Ruto³ | Gary Bosworth⁴ | Simon Pearson¹

¹Lincoln Institute for Agri-Food Technology, University of Lincoln, Lincoln, UK

²Collison and Associates Ltd, Tilney All Saints, Kings Lynn, Norfolk, UK

³Lincoln International Business School, University of Lincoln, Lincoln, UK

⁴School of Geography, University of Lincoln, Lincoln, UK

Correspondence

Iain J. Gould, Lincoln Institute for Agri-Food Technology, Riseholme Campus, University of Lincoln, Riseholme Park, Lincoln LN2 2LG, UK.
Email: igould@lincoln.ac.uk

Funding information

University of Lincoln

Abstract

Under future climate predictions, the incidence of coastal flooding is set to rise. Many coastal regions at risk, such as those surrounding the North Sea, comprise large areas of low-lying and productive agricultural land. Flood risk assessments typically emphasise the economic consequences of coastal flooding on urban areas and national infrastructure. Impacts on agricultural land have seen less attention, and considerations tend to omit the long-term effects of soil salinity. The aim of this study is to develop a universal framework to evaluate the economic impact of coastal flooding to agriculture. We incorporated existing flood models, satellite acquired crop data, soil salinity, and crop sensitivity to give a novel and detailed assessment of salt damage to agricultural productivity over time. We focussed our case-study on low-lying, highly productive agricultural land with a history of flooding in Lincolnshire, UK. The potential impact of agricultural flood damage varied across our study region. Assuming typical cropping does not change postflood financial losses range from £1,366/ha to £5,526/ha per inundation, these losses would be reduced by between 35% up to 85% in the likely event that an alternative, more salt-tolerant, cropping, regime is implemented postflood. These losses are substantially higher than losses calculated on the same areas using established flood risk assessment framework conventionally used for freshwater flood assessments, with differences attributed to our longer term salt damage projections impacting over several years. This suggests flood protection policy needs to consider local and long-term impacts of flooding on agricultural land.

KEYWORDS

agricultural output, coastal flooding, financial impact, soil salinity

1 | INTRODUCTION

Coastal flooding has devastating consequences for millions of people, properties, and land worldwide (Nicholls, 2004; Jongman et al. 2012). Under future climate scenarios, including sea level rise and greater storm surge frequency, the extent of coastal flooding is set to increase

(IPCC, 2007; Nicholls & Cazenave, 2010; Brecht et al. 2012; Vousdoukas et al. 2016). The North Sea region of Europe is at particular risk, comprising many low-lying coastal areas with dense populations, key industrial hubs, and highly productive agricultural lands (Daliakopoulos et al., 2016; Raats, 2015). It is also a region with a long history of devastating sea floods (Wadey et al., 2015).

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Flooding already constitutes the most serious natural hazard facing the United Kingdom (Thorne, 2014). Over 6 million properties along with significant parts of the national infrastructure essential for power supply and transport (Department for Environment, Food, and Rural Affairs [DEFRA], 2012; Environment Agency [EA], 2014; Prime et al. 2015; Thorne, 2014) are at risk from coastal flooding (Nicholls & Cazenave, 2010). In the United Kingdom alone, the financial consequences are significant (see e.g., Penning-Rowsell, 2015) and formed the basis of a key economic assessment of the natural hazard risk and coastal defence strategy, leading to a planned UK investment of £2.5 billion in flood defences over 6 years to protect housing (UK Cabinet Office 2017). However, the economic impact of coastal flooding to agricultural land has received little attention, understandably as most impact assessments have tended to focus on urban rather than rural locations. Nevertheless, large proportions of the most productive agricultural land occupy low-lying, reclaimed coastal regions. These areas are not only susceptible to coastal flooding climate scenarios (Lowe & Gregory, 2005; Spencer et al. 2015), but the risk has manifested in recent history; in particular, the North Sea storm surges of 1953, 1978, and 2013 resulted in widespread farmland inundation and crop losses along the east coast of England and low-lying coastal regions including the Netherlands (Steers et al. 1979; Baxter, 2005; Spencer et al., 2015).

In addition, although soil salinization is one of the major contributors to worldwide soil degradation (Food and Agriculture Organization [FAO], 2015; United Nations, 2017), it has been of little historic concern in temperate maritime climates. In these regions, through the medium term (1 to 7 years), salts are flushed through the soil profile by relatively high rainfall and low evaporation rates (Abrol et al. 1988). However, future predictions of coastal flooding suggest salt damage could become an increased occurrence (Gregory et al., 2015; Lowe et al., 2009; van Weert, van der Gun, & Reckman, 2009). Furthermore, saline intrusion of groundwater aquifers, exacerbated by a predicted increase in water abstraction and rising sea levels may increase exposure to brackish water sources (van Weert et al., 2009; Werner et al., 2013). Coastal farmland can potentially also be exposed to salt spray from high tides encroaching on banks (Rozema et al., 1983; McCune 1991). As such, it is essential to develop a quantitative and detailed understanding of potential coastal flooding and salinization impacts on agricultural productivity in high risk regions.

Coastal flooding of farmland can lead to immediate, as well as long term, crop losses. Even after flood waters recede, salt deposition from sea water establishes a legacy of soil salinity (Dasgupta et al. 2015), negatively affecting the growth of many crops with long-term impacts on soil structure (Shainberg & Letey, 1984). The scale of impacts is likely to be a function of inundation depth, duration, and seasonality (Chadwick et al. 2015; Sjøgaard et al. 2017). Seasonality plays an important role when estimating flood damage to crops and the implications for postflood management and crop replacement (Penning-Rowsell et al. 2015). Determination of salinity risk to crop production is not straightforward, because flood risk varies by region, and crop type can vary significantly between and within different locations. Crop species can have widely varying tolerances to salinity.

In general, high salt levels reduce plant nutrient uptake (Abrol et al., 1988), but the extent depends on species-specific salt tolerance, for example, sugar beet and barley are considered more tolerant than brassicas and potatoes (Tanzi & Kielen, 2002). Furthermore, sodium ions disperse clay particles, with detrimental effects to soil physical properties (Frenkel, Goertzen, & Rhoades, 1978; Levy & Torrento, 1995; Paes et al., 2014) and can be retained in soils for a number of years depending on soil type and post-flood management (Qadir et al., 2001). If not subjected to significant management adaptation, evidence suggests that some inundated fields with significant clay fractions and/or restricted drainage, such as alluvial soils, may not revert to pre-flood production levels for up to 7 years (National Farmers Union, 2013; Roughton, 1993). Mitigation measures could include gypsum application, switching to a more salt-tolerant rotation, or even using grass leys to improve soils structure and salt-flushing potential (Six et al., 2004; Haruna et al., 2017). Loss of production following a natural hazard will have even wider negative consequences on the local economy and along the food value chain (FAO, 2015).

To reduce the incidence of coastal flooding in the United Kingdom, shoreline management plans have been implemented by the EA, and analogous approaches are undertaken globally. Such approaches review the economic viability of any protection measure, because construction and maintenance of a defence system come at significant cost. In the United Kingdom, a modelling and decision support framework is employed to assess potential losses based on residential and commercial property values (DEFRA, 2011). The value of farmland used in assessments, in accordance with the UK Treasury guidance, is based on land values, without considering contrasts in high-value crop outputs or their resilience to salinity impacts and localised supply chain economic and strategic impacts (DEFRA, 2008, National Audit Office, 2014, HM Treasury, 2018). Furthermore, although fluvial and coastal floods may cause similar scale and immediate damage to property during a flood, the postinundation damage by salts to agricultural soils is persistent for many years. Consequently, any framework built to compare coastal with fluvial flood damage without considering postflood recovery duration could underestimate saltwater damage caused to agricultural land. The economic benefits of coastal defences in rural areas may be undervalued.

The subject of salinization in Northern Europe has received little attention in the literature. However, the probability of sea flooding and saline ingress presented by future climate scenarios presents a significant threat. In this study, we aim to (a) develop a novel framework for estimating the impact of coastal (saline) flooding on agricultural production, (b) place this in context with existing frameworks and discuss implications for flood risk policy, (c) assess the impacts of postflood farm management choices on reducing this saline flood damage, and (d) use this to determine the agricultural losses of a coastal flood in coastal Lincolnshire, United Kingdom.

We first describe a technique for utilising remote sensing data with flood mapping to produce estimates of crops types at susceptible to flooding, and then present a framework for assessment of salinity-induced yield losses and financial losses on farm, and potential wider economic impacts. The framework integrates potential complexity

caused by flood seasonality or postflood management and the wider impacts to the economy. We then discuss the implications of the novel framework, comparing with established assessments and comment on the financial implications of changes in postflood management, and the significance of the case-study site.

2 | MATERIALS AND METHODS

2.1 | Study area

Coastal flooding risks are significant within Greater Lincolnshire. The region contributes 10% of the country's agricultural output by value (Collison, 2014) and accounts for a quarter of the nation's Grade 1 Agricultural Land (Ministry of Agriculture, Fisheries, and Food, 1988). Two thirds of Lincolnshire's Grade 1 land falls within the UK Environment Agency's coastal flood model regions, notably on the deep silty and clayey marine alluvium soils of the Wallasea 2, Tanvats, and Wisbech associations (Hodge et al. 1984). In the south of the county lies The Wash, a large coastal inlet (615 km²) opening into the North Sea. On the northern aspect of The Wash, 3 to 4 m above ordnance datum banked sea defences protect areas of low-lying Grade I agricultural land renowned for the production of high-value vegetable and potato crops (Collison, 2014). There are between one and three separate layers of banks protecting the land, with different banks built at a range of dates from at least the 12th to 21st century (see Hallam 1965, Wheeler 2008, and modern Ordnance Survey maps). The region has been settled and farmed from the Roman era to present, and the environmental history of a significant proportion of the region is well described (Simmons, 2017). Detailed light detection and ranging maps are now available showing the topography of the region (Malone, 2014). Sectors along North Sea and The Wash front defences have been known to fail, most recently during the December 2013 storm surge event that reached 6.047 m above ordnance datum at nearby Kings Lynn (Simmons, 2017), where 200 ha of farmland and over 800 properties along The Wash were inundated (EA, 2014). As such, the agricultural areas surrounding The Wash region in Lincolnshire provides an ideal case-study for this assessment.

2.2 | Crop composition

To assess crop composition within flood scenario regions, we used 2016 Land Cover Plus ESRI shapefiles from the Natural Environment Research Council (NERC) Centre for Ecology and Hydrology for the three Lincolnshire local government districts surrounding the Wash Coast—East Lindsey, Boston, and South Holland districts (NERC, 2016). Land Cover Plus utilises satellite data from Copernicus Sentinel-1 C-band synthetic aperture radar and Sentinel-2 optical to generate crop maps at the field scale. The 2016 data included 11 field categories: 'winter wheat'; 'spring wheat'; 'winter barley'; 'spring barley'; 'beet'; 'field beans'; 'maize'; 'oilseed rape'; 'potatoes';

'grass'; and 'other.' The data benefit from access to extensive coverage of the United Kingdom, and validation against Rural Payments Agency (RPA) crop data has reported high accuracy for United Kingdom's dominant crops (oilseed rape winter cereals, grass) although has less accuracy in spring cereals (NERC, 2016), whereas the broad 'other' category would likely contain locally specific crops. Consulting local expertise and practice, alongside known RPA data, we allocated crops in the 'other' category were brassica vegetables, which are grown predominantly around The Wash region. These satellite crop data were overlain with our selected flood scenarios in ARCGIS.

2.3 | Flood scenarios

We selected three flood scenarios reflecting (a) current breach hazard, (b) future breach hazard, and (c) "big" flood event. Although we provide results from all three flood scenario analysis throughout the text and Data S1, the primary focus of the study discusses results from current breach hazard. For all breaches, we assume the postbreach regime is to repair the breach and continue the existing defence strategy.

2.3.1 | Current breach hazard

To assess current areas exposed to sea bank breach hazard, we used breach scenarios obtained from the UK Environment Agency (Scenarios E01-E34; W01-W33 Hazard Mapping Northern Area AN785: Composite Hazard). These flood scenarios are used to inform the UK flood defence strategy. They model the ingress of flood water for a 1 in 200-year breach (72-hr duration) of sea defences under 2006 climate conditions; 2006 is the most recent breach scenario data released by the EA, and as such, we describe as 'current'. We used breach scenarios from 67 individual locations spanning a 105-km stretch of Lincolnshire coastline (Figure 1), including breach scenarios in the tidal reaches of the River Haven. Information on each breach location width and defence type is detailed in Table S1. For an example of breach shape and extent of farmland affected by a breach, see Figure S2. To account for localised differences in tidal behaviour, we grouped these 67 model scenarios into four coastal zones (Figure 1). These were (North to South): Coastal Zone 1 (CZ1)—northernmost zone stretching from Donna Nook to Gibraltar Point with an eastward facing North Sea coast towards (35 scenarios); Coastal Zone 2 (CZ2)—the North West coast of The Wash, spanning the distance between Gibraltar Point and the mouth of The Haven (9 scenarios); Coastal Zone 3 (CZ3)—breach scenarios along the banks of the tidal Haven River by Boston (19 scenarios); and Coastal Zone 4 (CZ4)—the extent of The Wash coastline between the River Welland and River Nene in the south of the County (3 scenarios; Figure 1). Using 2016 Land Cover Plus data (NERC, 2016), average crop composition per breach area was

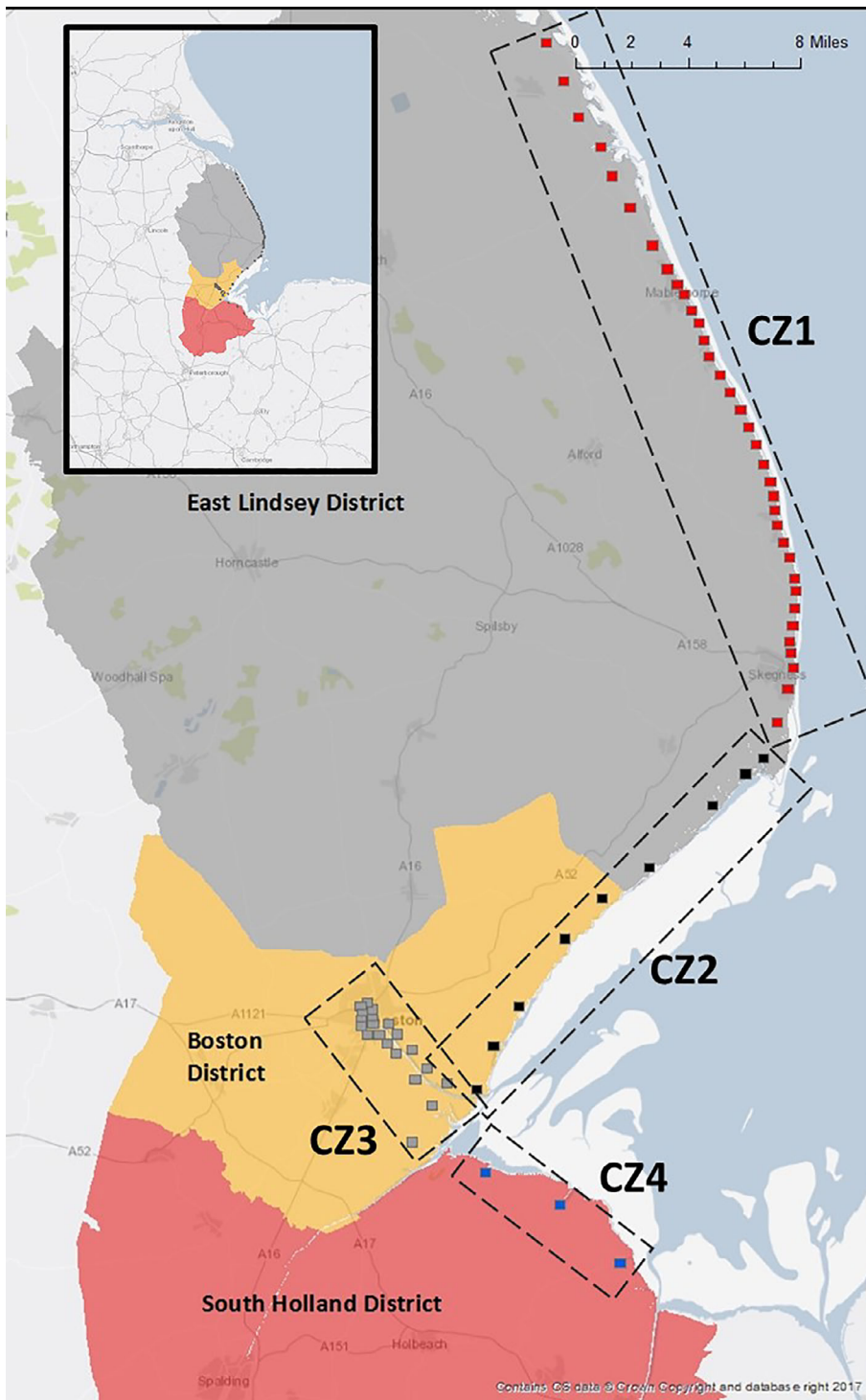


FIGURE 1 The location of each analysed breach scenario, coastal zone (CZ), and district within the study area. Red squares represent breach locations in CZ1, black squares represent breach locations in CZ2, grey squares represent breach locations in CZ3, and blue squares represent breach locations in CZ4

calculated for each of the four coastal zones, giving a typical breach crop composition for each stretch of coastline.

2.3.2 | Future breach hazard

The EA also provides breach area under 2115 climate prediction scenarios. Given the unpredictability of future breach hazard models, we

predominantly focus on 2006 breach data within this study, with 2115 results provided in Table S3.

2.3.3 | Large flood event

To compare the breach scenarios to an extreme flood event ('big event'), we also overlaid crop data with EA Flood Map for Planning

(Rivers and Sea)—Flood Zone 3. This is a flood scenario based on a 1 in 200-year sea flood whereby the protection offered by coastal defences are not factored in (see <https://data.gov.uk/dataset/flood-map-for-planning-rivers-and-sea-flood-zone-3>).

2.4 | Financial impacts of salinity on farm

2.4.1 | Soil salinity and postflood yield recovery

Seawater flooding impacts on yield can occur over many years. Therefore, to assess total yield loss (current and future years) as the soil recovers, we first calculate the response of different crop types (relative yields) to salt-affected land. In this study, we do this by predicting salt-soil levels in recovery years. For a more detailed farm-scale assessment, this method could be adapted by inputting known or historic salt levels. We assumed the complete loss of the standing crop during the flood (zero yield in flood year) followed by a recovery in subsequent harvest's yield, where the rate of recovery is a function of the salt tolerance per crop type based on predicted salt-soil levels. Thus, the model considers that highly tolerant crops recover yield on inundated fields at a faster rate than sensitive crops.

The length of time a soil takes to recovery from salts will depend on soil type; for example, a well-drained sandy soil may recover back to postflood production in 2 years, whereas a heavier, poorly drained soil may take up to 7 years. As such, without knowledge of site specific drainage regimes, we modelled six recovery scenarios for 2 to 7 years (harvests) soil recovery. The first step of the model is to predict crop relative yields, in each year, based on the model derived from FAO crop salt tolerance data (Maas & Hoffman, 1977; Tanji & Kielen, 2002):

Calculating expected relative crop yields for saline soils:

$$Yr = 100 - b(ECe - a) \quad (1)$$

Where Yr is the relative crop yield in a given year relative to the expected nonflooded yield; a is the crop salinity threshold in decisiemens per metre; b is the slope expressed in percent per decisiemens per metre; and ECe is the predicted (or measured) salinity level (dSm^{-1}) of soil at any given recovery year. Values for a and b for each crop are given in Tanji & Kielen (2002) whilst ECe originates from the mean electrical conductivity of a saturated paste taken from the rootzone, measured in dSm^{-1} . Our review of the literature found little data available for such salt retention levels in UK agricultural soils over time. For this study at a regional scale, we estimated values for ECe using immediate postflood (high) salt levels of $7.1 dSm^{-1}$, a typical postflood value recorded in previous saline flooding research in UK North Sea coastal systems (Hazelden & Boorman, 2001), and “recovered” salt values of $1.6 dSm^{-1}$, a level where no yield penalty is expected on any of the crops, in n year (n = salt recovery time) with a linear reduction of salt levels between the two. We note that this estimation of salt levels is a potential source of error in assessing the impact to yields, which is why we model a range of recovery

scenarios, and the model has the potential for the incorporation of actual soil salinity measurements if these become available in future. See Table 1 for details of our predicted salt levels per recovery year harvest, and expected yield penalties based on penalty expected from FAO crop salt tolerance data. We calculated relative yields within each recovery year harvest for all 6 recovery scenarios.

2.4.2 | Impacts to yield

To assess yield impact, reference data for yield per hectare were obtained from the John Nix Farm Management Pocketbook (Redman, 2020). Such values are based on projected, rather than recorded, prices, but are often used for financial assessments of UK farmland (e.g., in Glithero et al. 2013; Austin et al. 2015). As a method of yield sensitivity analysis we present output values given from the range of high, average and low yielding scenarios given in Nix for each breach, and assumed crops in the Land Cover Plus ‘other’ category were brassica vegetables reflecting local practice (Rural Payments Agency, 2016). Total tonnage lost of each crop in each recovery year harvest was calculated from the following formula:

Expected saline yield losses in each recovery year harvest:

$$LY_x = (h \times Y_{FM}) \times \left(\frac{100 - Yr_x}{100} \right) \quad (2)$$

Where LY_x is the loss in yield (tonnes) in recovery year harvest x (i.e., harvests 1 to 7); h is the hectare coverage of each crop within each breach scenario; Y_{FM} are the Farm Management Pocketbook yield per hectare values for each crop (Redman, 2020); and Yr_x is the relative yield for recovery year harvest x , based on salinity and crop tolerance derived in Equation (1).

2.4.3 | Financial impacts

Financial losses will depend on the seasonality of a flood. In the UK, over the course of a year monthly probability of coastal flooding peaks in two seasonal periods: autumn/early winter and spring (Roca et al. 2011). We construct two models based on these two seasonal periods based on the following assumptions: (a) flooding in autumn/early winter would still destroy a crop but would allow time for drilling a spring crop soon after; (b) conversely, a spring flood would not only destroy a spring crop but also deny establishment of any replacement crops that season. We refer to an autumn/early winter flood as an early flood and a spring flood as a late flood.

For an early flood, the initial crop is lost, but some variable costs would be spared (sprays and harvest costs) and overall losses may be minimised if a farmer can drill a spring crop after. As such, initial losses from an early flood (flood year—first harvest only) are estimated with Equation (3a):

Financial losses from an early flood—flood year (Year 0) only:

TABLE 1 Predicted salt-soil levels and yield penalties in each recovery scenario

Soil recovery scenario	Predicted soil salt levels (dSm ⁻¹)	Saline yield penalty (% crop loss)										
		Beet	Field beans	Grass	Maize	Oilseed rape	Other (brassica)	Potatoes	Spring barley	Spring wheat	Winter barley	Winter wheat
7-year recovery												
Flood year	Flood	100	100	100	100	100	100	100	100	100	100	100
Harvest 2	7.1	1	53	11	65	0	45	65	0	8	0	8
Harvest 3	6	0	42	3	52	0	35	52	0	0	0	0
Harvest 4	4.9	0	32	0	38	0	25	38	0	0	0	0
Harvest 5	3.8	0	21	0	25	0	14	25	0	0	0	0
Harvest 6	2.7	0	11	0	12	0	4	12	0	0	0	0
Harvest 7	1.6	0	0	0	0	0	0	0	0	0	0	0
6-year recovery												
Flood year	Flood	100	100	100	100	100	100	100	100	100	100	100
Harvest 2	7.1	1	53	11	65	0	45	65	0	8	0	8
Harvest 3	5.7	0	39	1	48	0	32	48	0	0	0	0
Harvest 4	4.3	0	26	0	32	0	19	32	0	0	0	0
Harvest 5	3.0	0	13	0	15	0	6	15	0	0	0	0
Harvest 6	1.6	0	0	0	0	0	0	0	0	0	0	0
5-year recovery												
Flood year	Flood	100	100	100	100	100	100	100	100	100	100	100
Harvest 2	7.1	1	53	11	65	0	45	65	0	8	0	8
Harvest 3	5.3	0	35	0	43	0	28	43	0	0	0	0
Harvest 4	3.4	0	18	0	21	0	11	21	0	0	0	0
Harvest 5	1.6	0	0	0	0	0	0	0	0	0	0	0
4-year recovery												
Flood year	Flood	100	100	100	100	100	100	100	100	100	100	100
Harvest 2	7.1	1	53	11	65	0	45	65	0	8	0	8
Harvest 3	4.4	0	26	0	32	0	19	32	0	0	0	0
Harvest 4	1.6	0	0	0	0	0	0	0	0	0	0	0
3-year recovery												
Flood year	Flood	100	100	100	100	100	100	100	100	100	100	100
Harvest 2	7.1	1	53	11	65	0	45	65	0	8	0	8
Harvest 3	1.6	0	0	0	0	0	0	0	0	0	0	0
2-year recovery												
Flood year	Flood	100	100	100	100	100	100	100	100	100	100	100
Harvest 2	1.6	0	0	0	0	0	0	0	0	0	0	0

Note: Salt levels based on a linear decline function as detailed in Section 2. Yield penalty calculated from FAO crop salt tolerance data (Maas & Hoffman, 1977; Tanji & Kielen, 2002) for spring flood scenario, where all crop is assumed lost (100%) in flood.

$$LF_{fy} = LY_0 \times P - (h \times SV_{\text{fert + spray + labour + harvest + transport + other}}) \quad (3a)$$

Where LF_{fy} are the financial losses (£) in the flood year; LY_{fy} is the loss in yield calculated from Equation (2); P is the market price of the crop (£/t); h is the hectare coverage of each crop within each breach scenario; SV is the saved variable costs—the total of any variable costs, per hectare, avoided by crop replacement (e.g., fertiliser, sprays, labour, harvest, and transport costs). Here, we assume yield losses in the flood year (Harvest 1) will be total. For further harvests in the

early flood scenarios (Harvests 2 up to 7), we refer to Equation (3c), where Harvest 2 will be drilled the following spring (Figure 2).

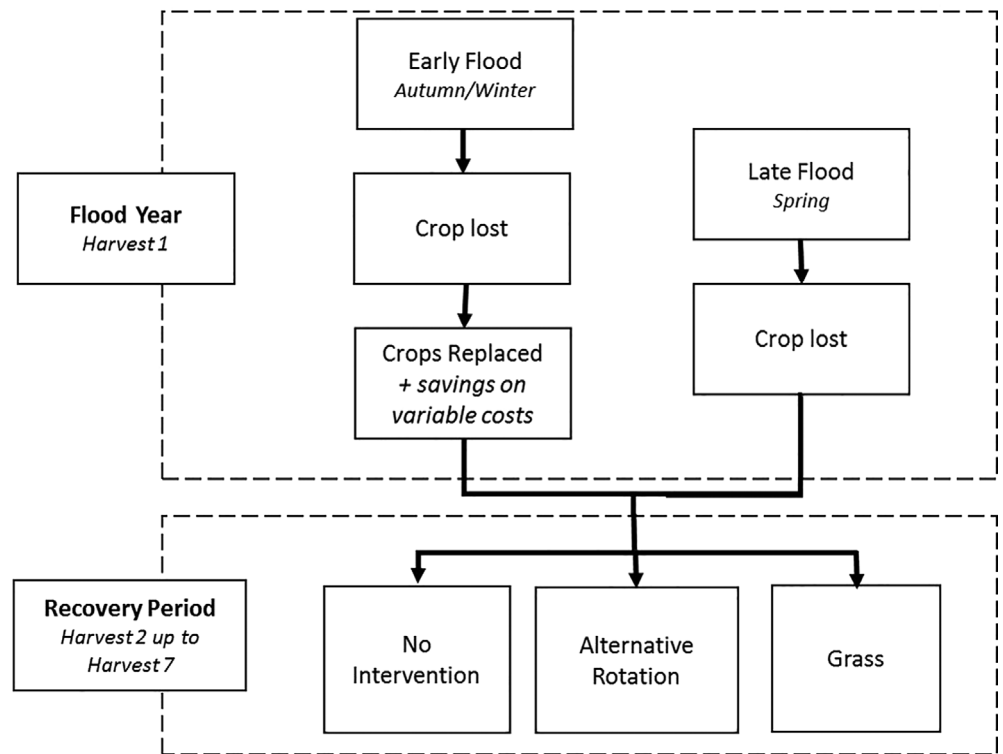
For a late flood, the crop is lost but assume no crop replacement savings that year and thus greater net losses:

Financial losses from a late flood—flood year (Year 0) only:

$$LF_{fy} = LY_{fy} \times P \quad (3b)$$

Where LF_{fy} are the financial losses (£) in the flood Year x ; LY_{fy} is the loss in yield in flood year calculated from Equation (2); P is the

FIGURE 2 Model process for an early flood and late flood



market price of the crop (£/t). Subsequent crop yield penalties in future harvests are calculated the same for an early flood as for a late flood. These build on Equation (3b), assume the yield penalties reported in Table 1, and future projections are discounted from the base year (flood year) at the Treasury discount rate of 3.5%.

Financial losses in recovery years after flood:

$$LF_x = LY_x \times P \times \frac{1}{1.035^x} \quad (3c)$$

Where LF_x are the financial losses (£) in recovery Year x ; LY_x is the loss in yield in recovery Year x for a particular crop (see Crop Choice in Recovery Years); P is the market price of the crop (£/t). In this study, we calculate recovery year financial losses from all recovery scenarios (i.e., assuming soils take from 1 harvest to recover up to 7 harvests to recover) but report on the most likely recovery situation for each soil type in the discussion.

2.4.4 | Crop choice in recovery years

It is likely that postflood decisions could lead to a change in crop selection in recovery years, which would influence the inputs in Equation (3c). To assess how changes to crop choice could influence farm finances postflood, we model three scenarios, as outlined in Figure 2 to represent potential farmer choice: (a) 'no intervention'—growing the same crop composition after the flood; (b) 'alternative rotation'—growing only the more salt tolerant crops; or (c) 'grass'—putting land down to grass. We select these three options as all three

strategies were found to be adopted by farmers inundated in the 2013 storm surge in Lincolnshire.

i. No intervention

Here, we assume the farm will continue with typical cropping as pre-flood, potentially suffering at a yield penalty on these up to Harvest 7. For the early flood scenario, only spring sown crops are used for Harvest 2 only, the areas of which are calculated by dividing the total area of winter crops found in the specific breach equally between spring crops.

ii. Alternative rotation

For the alternative rotation scenario, we assume the farmer no longer plant the more sensitive crops such as field beans, maize, brassica, and potatoes (Tanji & Kielen 2002). Within each breach area scenario, the total area for these sensitive crops is divided equally between additions to total hectares of sugar beet, oilseed rape, barley, and wheat. For the second harvest only of an early flood scenario, only spring sown crops are used as above.

iii. Grass

In this scenario, the assumption is that all crop area within the breach zone is put down to grass in the recovery years. Our study region is in a predominantly arable region, and as such, we obtain financial values for grass values assuming grazing (Redman 2020). Further detailed assessments of grassland loss calculations, can be found in Penning-Rowsell (2013).

2.5 | Economic impacts to the wider agri-food sector

With an estimate of the farm level financial damage of the flood, we then look into the wider impacts for the first year of flooding, assume that all crops are lost as in original model. This approach may not account fully for additionally or displacement effects of supply chain resilience but takes a broad approach for regional scale assessment. All values obtained from Redman (2020) unless otherwise stated. As before, we calculated for the £/ha range of high, average, and low outputs provided in Redman (2020) to represent a yield sensitivity analysis. For direct farm impacts, we used the gross margins of each crop area per breach (Redman 2020). The total of these per breach were multiplied by the gross value added per agricultural employee, taken as £30,000 using the regional agri-food sector plan (Collinson 2014) to estimate the number of jobs supported per breach area. To estimate the impact on suppliers, the total variable costs of each crop per breach were converted to jobs, we divided this by the input value per sector job (£267,000; £14.95 billion divided by 56,000 jobs; DEFRA, 2016).

2.6 | Comparison with established flood assessments

We compared our model outputs with those of an established model of flood risk assessment in the United Kingdom—Flood and Coastal Erosion Risk Management Manual (Penning-Rowsell et al., 2013). This framework predominantly focuses on freshwater floods, with estimated yield losses (p. 340) dependant on seasonality, with suggested further yield penalties for coastal flooding (p. 329) per crop type. These were combined for our comparison assessment, to give estimated yield losses for a coastal flood within our two seasonal periods (early flood and late flood). To compare early flood scenarios, we used the given expected average yield penalties from September to November and February to April for late flood scenarios. Financial losses on farm were then calculated using the ARABLE equation (p. 339), which estimates financial damage based on yield penalties, market price, and potential savings in input and harvest costs. Penning-Rowsell (2013) also provides a comprehensive assessment for livestock assessment, but for our predominantly arable case-study region, we focus on the ARABLE model, using grazing grass values (Redman, 2020) for grass areas.

3 | RESULTS

3.1 | Areas of individual crops within each coastal zone breach areas

The extent of land covered by each breach scenario varied between coastal zones. The largest breach area averages were located in the south of the county along the north-east (CZ2; 2,950 ha) and south-

east (CZ4; 5,242 ha) facing coasts of The Wash (Table 1). Less extensive breach areas were found in the northern stretch of the study site, CZ1 (1,962 ha), and the tidal banks of the River Haven in CZ3 (1,460 ha; Table S1). In the big event flood scenario, the total inundation is 108,239 ha. Coastal zones also showed substantial differences in crop composition (Table 2). Key differences include the larger areas of grass (18%; 369 ha) and lower potato areas (<1%; 10 ha) in CZ1 compared with the other zones. Winter wheat was prominent across all coastal zones, constituting 22–39% (342–2,017 ha) of breach areas (Table 2).

3.2 | Salinity tolerance and crop composition between coastal zones and inland districts

To assess whether there were variances between the relative salt tolerance of crops grown between the different coastal zones, we categorised each crop type into one of three salinity categories according to FAO crop salinity tolerance indices (Tanjil & Kielen, 2002), which were moderately sensitive (field beans, maize, brassicas, and potatoes), moderately tolerant (grass and wheat), or tolerant (beet, oilseed rape, and barley). We found that the moderately salt tolerant and salt tolerant crops occupied a high proportion (85%) of CZ1, whereas in the other coastal zones the breach area contained moderately salt-sensitive crops (56% of land area in CZ2; 48% in CZ3; and 45% in CZ4; Figure 3).

3.3 | Impacts of salinity on yield and financial output

In the flood year alone, a breach flood could destroy a total crop output potential from 13,720 t in a low yielding but up to 16,816 t in a high yielding scenario in CZ1, 50,002 t in a low yielding to 61,352 t in a high yielding scenario in CZ2, 21,527 t in a low yielding to 26,279 t in a high yielding scenario in CZ3, and 83,562 t in a low yielding to 105,270 t in a high yielding scenario in CZ4. When these are converted to potential financial losses, in the flood year alone, this translates to between £600/ha (low yield and early flood) to £1,430/ha (high yield and late flood) in CZ1, £1,352/ha (low yield and early flood) to £3,513/ha (high yield and late flood) in CZ2, £1,202/ha (low yield and early flood) to £3,074/ha (high yield and late flood) in CZ3, and £1,179/ha (low yield and early flood) to £3,172/ha (high yield and late flood) in CZ4 (Table 3).

Beyond the flood year, losses in the recovery period will depend on flood seasonality, postflood farm management, yield potential, and soil drainage (salt recovery). The model produced estimates for losses for all of these scenarios (Table 3). From here, we report financial loss estimates for each coastal zone based on given knowledge of the soil types and cropping in our specific case-study areas.

The heavier soils of CZ1 (Wallasea 2 association) may expect poorer drainage (7-year recovery scenario) and average yield conditions, and thus, the likely prediction is financial losses of £1,366/ha in an early flood and £1,940/ha in a late flood if the farm crop choice remains

TABLE 2 Area of each crop in average breach area within each CZ. Results displayed in both total hectares and percentage of breach area occupied by particular crop. Crops in italics are deemed salt sensitive crops (Tanji & Kielen 2002)

	CZ 1		CZ 2		CZ 3		CZ 4	
	(ha)	%	(ha)	%	(ha)	%	(ha)	%
Beet	8	0.4	250	8.5	98	6.7	381	7.3
<i>Field beans</i>	70	3.6	24	0.8	23	1.6	54	1.0
Grass	369	18.8	111	3.8	118	8.1	55	1.0
<i>Maize</i>	10	0.5	62	2.1	12	0.8	95	1.8
Oilseed rape	252	12.8	93	3.2	44	3.0	105	2.0
<i>Other (brassica)</i>	173	8.8	1,316	44.6	565	38.7	1,641	31.3
<i>Potatoes</i>	10	0.5	269	9.1	98	6.7	541	10.3
S. Barley	163	8.3	55	1.9	46	3.2	148	2.8
S. Wheat	92	4.7	59	2.0	93	6.4	64	1.2
W. Barley	160	8.2	45	1.5	19	1.3	139	2.7
W. Wheat	653	33.3	666	22.6	341	23.4	2017	38.5
Total	1,962		2,949		1,459		5,242	

Note: Results displayed in both total hectares and percentage of breach area occupied by particular crop. Crops in italics are deemed salt-sensitive crops (Tanji & Kielen 2002).

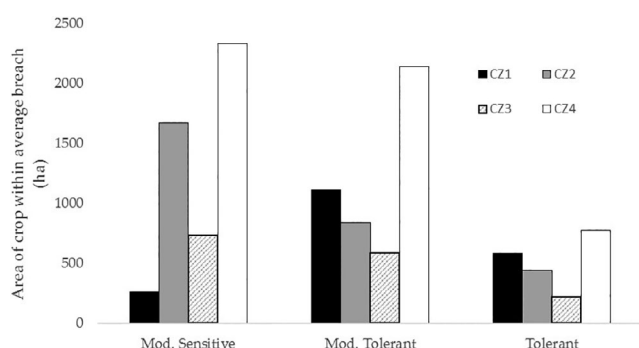


FIGURE 3 Showing average crop area of each coastal zone breach, categorised by crop salt tolerance

unchanged (no intervention scenario). With a switch to alternative, salt tolerant cropping, the model estimates losses of £778/ha in an early flood and £1,352/ha in a late flood. With the third scenario, giving the field up to grass grazing, estimated losses are £741/ha in an early flood and £1,316/ha in a late flood. Indicative flood assessments based on an established flood risk model (Penning-Rowsell et al. 2013) gave loss estimates of £255/ha in an early and £433/ha in a late flood.

CZ2 is on a Grade 1 silt soil (Wisbech association), and we expect these zones to fall under the high yield and medium drainage/soil recovery conditions (4-year recovery). As such, the model predicts financial losses in CZ2 of £3,660/ha (early flood) and £5,526/ha (late flood) in the no intervention scenario, £1,717/ha (early flood) and £3,584/ha (late flood) in the alternative rotation scenario, and £1,655/ha (early flood) and £3,521/ha (late flood) in the grass scenario. These compare with losses of £1,158/ha (early flood) and £1,184/ha (late flood) based on established flood risk model estimates.

We would typify CZ3 as average yield and medium recovery (Tanvats association). The model predicts financial losses in CZ3 of £2,943/ha (early flood) and £4,527/ha (late flood) in the no

intervention scenario, £1,400/ha (early flood) and £2,983/ha (late flood) in the alternative rotation scenario, and £1,347/ha (early flood) and £2,930/ha (late flood) in the grass scenario. These compare with losses of £917/ha (early flood) and £970/ha (late flood) based on established flood risk model estimates.

CZ4, like CZ2, is on a Grade 1 silt soil (Wisbech association), and thus, we estimate under the high yield and medium drainage/soil recovery conditions. The model predicts CZ4 financial losses of £3,264/ha (early flood) and £4,887/ha (late flood) in the no intervention scenario, £1,631/ha (early flood) and £3,256/ha (late flood) in the alternative rotation scenario, and £1,556/ha (early flood) and £3,181/ha (late flood) in the grass scenario. These compare with losses of £922/ha (early flood) and £1,091/ha (late flood) based on established flood risk model estimates.

Across the coastal zones, the financial losses were substantially reduced in the alternative cropping and grass scenarios. Compared with the no intervention scenario, these managements would reduce losses by 74–85% in CZ1, 35–70% in CZ2, 43–73% in CZ3, and 42–72% in CZ4, depending on soil recovery time (Table 3).

We estimate some of the wider impacts to suppliers and potential job losses at the supplier and direct farm and supplier level (Table 4), which show potential job losses for farming business and the supplier network. These range from 34 to 50 jobs in CZ1, 99 to 129 jobs in CZ2, 44 to 57 jobs in CZ3, and 161 to 226 jobs in CZ4.

4 | DISCUSSION

4.1 | Development of a framework for coastal flood impact assessment to agricultural land

The impact of coastal flooding on agriculture has seen little attention in the literature, and no assessment has accommodated the multiyear

TABLE 3 Financial losses per ha (£/ha) based on in the average breach crop composition in each coastal zone (CZ1–CZ4) for a range of postfarm management scenarios

Coastal zone and postflood farm management strategy		Good drainage potential 2-year recovery		Medium drainage potential 4-year soil recovery		Poor drainage potential 7-year soil recovery	
		Early flood	Late flood	Early flood	Late flood	Early flood	Late flood
CZ1	No intervention			£1,090 ± 13%	£1,665 ± 9%	£1,366 ± 11%	£1,941 ± 8%
	Alt. rotation	£731 ± 18%	£1,306 ± 10%	£777 ± 18%	£1,352 ± 10%	£778 ± 18%	£1,352 ± 10%
	Grass			£740 ± 18%	£1,315 ± 10%	£742 ± 18%	£1,317 ± 10%
	MCM comparison	£255 ± 24%	£433 ± 11%	£255 ± 24%	£433 ± 11%	£255 ± 24%	£433 ± 11%
CZ2	No intervention			£3,431 ± 7%	£5,273 ± 5%	£5,084 ± 6%	£6,926 ± 5%
	Alt. rotation	£1,502 ± 10%	£3,343 ± 5%	£1,563 ± 10%	£3,405 ± 5%	£1,563 ± 10%	£3,405 ± 5%
	Grass			£1,510 ± 10%	£3,352 ± 5%	£1,512 ± 10%	£3,354 ± 5%
	MCM comparison	£1,073 ± 8%	£1,106 ± 7%	£1,073 ± 8%	£1,106 ± 7%	£1,073 ± 8%	£1,106 ± 7%
CZ3	No intervention			£2,944 ± 7%	£4,527 ± 5%	£4,307 ± 6%	£5,890 ± 5%
	Alt. rotation	£1,339 ± 10%	£2,922 ± 5%	£1,400 ± 10%	£2,983 ± 6%	£1,400 ± 10%	£2,984 ± 6%
	Grass			£1,347 ± 10%	£2,931 ± 5%	£1,349 ± 10%	£2,933 ± 5%
	MCM comparison	£917 ± 8%	£970 ± 7%	£917 ± 8%	£970 ± 7%	£917 ± 8%	£970 ± 7%
CZ4	No intervention			£2,986 ± 10%	£4,583 ± 7%	£4,370 ± 8%	£5,967 ± 7%
	Alt. rotation	£1,367 ± 14%	£2,964 ± 7%	£1,440 ± 14%	£3,038 ± 7%	£1,440 ± 14%	£3,038 ± 7%
	Grass			£1,375 ± 14%	£2,973 ± 7%	£1,377 ± 14%	£2,975 ± 7%
	MCM comparison	£818 ± 13%	£997 ± 10%	£818 ± 13%	£997 ± 10%	£818 ± 13%	£997 ± 10%

Note: Financial losses per ha (£/ha) based on in the average breach crop composition in each coastal zone (CZ1–CZ4) for a range of postfarm management scenarios: (a) no intervention, (b) alternative rotation, and (c) grass. Also presented is the results of comparison with established flood risk assessment (MCM—Penning-Rowse et al. 2013) Results presented are £/ha based average yield potential (Redman 2016), with percentage error representing deviance from low and high yields. We present results for good recovery (2 years), medium recovery (4 years), and poor recovery (7 years) soil drainage scenarios. In the good recovery scenario, normal cropping resumes in harvest after flood, thus no difference in postflood management.

and long-term impacts of saline ingress on productivity following a flood or the impacts on locally adapted production systems. We attribute this to a general lack of widespread salinity data in maritime climates (FAO, 2015; Daliakopoulos et al. 2016). Here, we present a novel model based on salt-soil levels and crop composition within flood affected areas.

The value of flooded farmland used in accordance with UK Treasury flood risk guidance is based on a combination of land suitability and land use, and conventional flood risk manuals (Penning-Rowse,

2013) predominantly focus on freshwater flooding impacts to crops. Penning-Rowse (2013) does, however, include yield penalties for saline water flooding that increase losses an additional 10% to 100% loss, depending on seasonality of flooding but do not manifest projections of damage in subsequent years. Estimate losses of our breach areas based on Penning-Rowse (2013) range from £255/ha to £1,184/ha. Other studies have presented actual damage costs from 1 year impacts; in freshwater flood events in the United Kingdom, damage costs range from £1,200/ha in the 2007 summer floods

TABLE 4 Jobs and costs to gross margins or gross value added on direct farm impacts and supplier impacts given a single year flood event

	At risk	CZ1	CZ2	CZ3	CZ4	Big event
Direct farm impacts	Jobs	28–45	72–101	33–46	120–185	2,118–3,182
	GM (£)	£848,000	£2,172,000	£975,000	£3,611,000	£63,537,000
		£1,346,000	£3,038,000	£1,368,000	£5,548,000	£95,465,000
Impact on suppliers	Jobs	5	27	11–12	40–42	602–613
	GVA (£)	£311,000	£1,535,000	£655,000	£2,309,000	£34,368,000
		£312,000	£1,566,000	£667,000	£2,369,000	£35,003,000
Total	Jobs	34–50	99–129	44–57	161–226	2,720–3,795
	Losses	£1,159,000	£3,707,000	£1,630,000	£5,921,000	£97,905,000
		£1,659,000	£4,604,000	£2,035,500	£7,918,000	£130,468,000

Note: Jobs and costs to gross margins (GM) or gross value added (GVA) on direct farm impacts and supplier impacts given a single year flood event. Based on average breach data for each coastal zone, in addition to big event scenario. Range in values represents variation in calculations based on low, average, or high yield outputs from land (Redman, 2020).

(Posthumus et al., 2009) to £710–1,130/ha in 2012 flooding (Morris & Brewin 2014), which map well with these 1 year flood damage estimates. Where our model differs is in considering longer term impacts beyond 1 year based on a salinity impact algorithm. We expect longer term impacts on many soils, particularly those with a high clay or silt content, which also tend to be the most agriculturally productive. Our model calculates likely losses ranging from £741/ha to £3,660/ha for an early flood and £1,316/ha to £5,526/ha for a later flood, depending on coastal location and postflood farm management. The broad range of these estimates are not yet empirically based, and speculate potential variation postfarm management strategies, which are shown to reduce financial losses. These results are notably higher than the conventional model estimates (Penning-Rowsell et al. 2013), reflecting two adaptations we have incorporated into our assessment, salt flood destruction of current crop and long-term impact of salts to soil function. This suggests that the potential damage caused to agriculture, particularly in high-value areas, has been under estimated until now. Our model assumes 100% crop loss after saline inundation, as was observed in the last UK coastal flood event, with long-term salt impacts to soils (Roughton 1993; National Farmers Union, 2013).

This framework provides a platform for risk assessment in regions where agricultural production represents a significant contribution to national production (Collison 2014). For example, in our case-study area, we show marked differences in flood resilience of coastal zones. Thus losses could potentially triple across a 105-km stretch of coast, a contrast which would not have been considered in any current framework based solely on land values (DEFRA, 2008, National Audit Office, 2014) or single year flood impacts. As such, this assessment could be utilised for decision-making in flood defence planning across rural areas where agriculture plays a vital role in the local economy. Furthermore, given future climate projections, the 1 in 200-year event will only be set to increase in frequency (Brecht et al. 2012; Voudoukas et al. 2016), further justifying a re-evaluation of the defence system.

4.2 | Changes to post-flood farm management

Alternative crop choices following a flood may not only minimise financial losses but could also contribute to greater salt removal and soil recovery. We find that substituting existing higher value, but salt sensitive, crops for more tolerant (albeit lower value) crops reduce the total financial damage of a flood in our region. Beyond this, switching crops could lead to a greater rate of salt removal and a return to 'normal' salt levels when conventional cropping resumes. We propose that improved soil recovery from crop choice arises through by three potential mechanisms.

4.2.1 | Salt removal through improved soil structure

Careful crop choice could improve soil structure and hydraulic conductivity, accelerating the salt-flushing rate through the action of roots (Oades 1984; Powlson et al. 2011). Given the expected water

damage to soils postflood, remedial action via roots may be more beneficial than remedial action, and potential structural damage, via heavy machinery. Such management could include prolific rooting crops, cover crops, or grass leys (De Baets et al. 2011; Isbell et al. 2017), preferably selected for beneficial traits, such as taproots, to assist in drainage. There is a growing body of work that has investigated beneficial root traits and plant communities to aid soil structure and thus flushing rates (Fischer et al. 2015; Gould et al. 2016; Isbell et al. 2017). However, to date, the authors do not know of any 'designer' cover, herbaceous or grassland mix that is tailor-made for salt-soil recovery. Development of such mixes could be combined with mineral amendments, such as gypsum, to remedy flooded soils. Given that we anticipate greater coastal flood incidence in future, this may warrant further investigation.

4.2.2 | Salt removal by uptake in crops

The previous option exploits a plant's ability to improve salt flushing down and out of the system through leaching. However, salts, specifically sodium, could also be removed from the system by plant uptake and removal off-site. Halophytes are plants that survive in saline environments and in many cases have the ability to store salt in their structures (Flowers & Colmer 2008; Flowers & Colmer 2015). Such attributes have given rise to interest in halophytes as both a future food source and a potential remediation tool to clean up saline soils, providing solutions to the growing problem of soil salinization globally (Ladeiro, 2012; Rozema & Schat, 2013; Panta et al., 2014; Hasanuzzaman et al., 2014). This could have potential in our case-study region; *Salicornia* occurs naturally around The Wash region; however, to our knowledge, it has never been grown commercially in the United Kingdom. A lower risk approach would be to plant a crop with a known market in the United Kingdom. One such solution could be sugar beet, which can uptake Na depending on K availability, potentially removing Na from the soil system (Draycott et al. 1970; Wakeel et al. 2010), but its widespread use would be dependent on local processing capacity.

4.2.3 | Reassessing crop salt tolerance

A third option is to ensure planting of conventional crops that could survive in the salt conditions without yield penalties, until salt levels have reduced enough to revert back to original cropping plans. Unlike some halophytes, these crops may not uptake the salts in their structures but still have the potential to exclude them from root uptake (Matsushita et al. 1991; Chen et al. 2018). In doing so, they are not directly acting to remove salts from the soil. However, in a maritime climatic region, they could be used in conjunction with natural leaching until salt levels have reduced postflood. One of the key limitations for this option is the lack of relevant data on crop salt tolerance in such climates. The majority of available data is based on arid and semi-arid conditions (Tanj & Kielen 2002), and original

development of such data was conducted in the Western United States, where the authors stress the need for caution when applying to other climatic regions (Ayers & Westcot 1985). Recent work in the Netherlands is starting to address this by screening conventional crop varieties for salt tolerance and refining methodologies to evaluate crop salt tolerance (de Vos et al. 2016; van Straten et al. 2019). Studies of soil salinization in northern maritime climates are few, but the future risk warrants further investigations on the subject. In our model, we calculate crop responses from assuming a linear salt-soil reduction over time, but the general lack of data in the North Sea region requires more investigation on salt deposition, salt retention, inundation depth impacts, and impacts to crops. Remediation strategies, as described, also need to be explored further in order to prescribe soil-specific best practice for salt removal.

4.3 | Impacts of coastal flooding on the case-study region

We demonstrate our framework in an area of the United Kingdom where high-value agriculture meets notable probability of sea flooding. However, the framework can be employed in any area, particularly where high value agricultural land finds itself susceptible to sea flood. Potential financial losses are a function of both geographical extent of flooding and typical crop composition (Tapia-Silva et al. 2011). The largest areas inundated by breach scenarios (CZ2 and CZ4) were located in areas that not only have large proportions of hinterland at, or below, sea level but also have frontages against The Wash—the bathymetry of which may contribute further to flood extent (Rossiter, 1954). The composition of crops within flood zones also changes along the coastline. With the exception of the northern CZ1, all other coastal flood zones had significantly high proportions of vegetable production. The majority of soils here are silty marine alluvium (Hodge, 1984), ideally suited for growing brassicas, notably towards the coast. Such higher commercial value crops also exhibit relatively high salt sensitivity, further exacerbating economic flood impact. In these southern regions surrounding The Wash (CZ2, CZ3, and CZ4) agriculture is also less resilient the further towards the coast, whereas the opposite is true of the CZ1 coast facing the North Sea, where less salt-sensitive crops dominate. Results in our study region mirror the difficulties facing global agriculture in coastal zones—fertile, productive agricultural land often corresponds with the most flood-prone regions of the globe (Gornall et al. 2010; Tockner & Stanford, 2002). It is also clear from this study that coastal flood risk must consider the local economic impacts, national estimates of crop loss from inundation may both overestimate or underestimate impacts, potentially leading to inappropriate flood defence prioritisation.

Our model shows that for agricultural output alone, a single sea wall breach could cost losses of up to £25 million (CZ4; £4,887/ha) in a high-value area, no intervention scenario. However, natural hazard impact assessments rarely assess the cascading impacts on the food value chain (FAO 2015). Physical damage of a coastal flood will not only affect the farmland but will have cascading negative

consequences both backward (e.g., fertiliser and machinery suppliers) and forward (e.g., processing and distribution) along the chain. The extent of economic damage will depend on whether the flood results in permanent disruption, such as a change in regional cropping. Based on the outputs of our wider agri-food economy assessment we could also expect significant job losses across the sector from a large flood. Assessing the wider impacts to the food supply chain has further complexity beyond that of jobs and value added. Food processing hubs often build up around agriculturally productive area, as is the case for our case-study region—home to the United Kingdom's main fresh produce hub (Collison, 2014). Once a flood reduces the supply of local raw materials, processing plants may be forced to move to other areas of the country, perhaps near ports where inputs are guaranteed. Furthermore, adaptations to crop selection following a flood will alter farm inputs. For example, shifting from less tolerant potatoes to more tolerant cereals can halve the tractor hours on farm (Redman, 2016) as well as reduced costs for other farm inputs such as seeds, fertilisers, and fuel with resultant impacts on local suppliers.

Furthermore, our 'big event' model, which depicts a 1 in 200-year coastal flood assuming no coastal defences, resulted in potential financial losses of £100 to £480 million, and yield losses of 1.3 to 2.5 million tonnes, which would have severe consequences for UK food security from our three districts alone. Historically, large parts of continental Europe have been devastated in such flood events (Baxter, 2005). Should our model be extended to other flood susceptible areas of Northern Europe; the substantial yield losses expected may also raise concern for regional food security.

5 | CONCLUSIONS

Our framework provides a novel platform for coastal flood risk assessment, presenting higher financial cost than previous estimates on account of the likely total destruction of any current crop, and incorporating the long-term impact of salt in the soil. Likely farmer responses could be to change cropping to more salt tolerant conventional crops or to graze fields for a number of years—two scenarios that would reduce financial losses per recovery year. When we apply the framework to our case-study region, financial losses could reach up to £4,887/ha in a single breach, which could result in substantial knock-on economic effects. Such a framework could be used to support sea defence prioritisation in regions such as this, where agricultural production represents a significant contribution to the local economy.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

ORCID

Iain J. Gould  <https://orcid.org/0000-0001-5315-2241>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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